Determinants of the Quality and Price of Innovative Industrial Products: Evidence from the Disk Drive Industry*

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Abstract

Using worldwide data from 1996-2010, this paper studies the causes of rapid quality improvement in disk drives. During this period storage capacity per drive increased by 375 times for desktop PCs and by 236 times for laptop PCs, where the capacity increase in mobile drives is understated by the miniaturization of laptops. Thus the price per Gigabyte (GB) of storage falls by a factor of 1304 in 2005 $ for desktops and slightly more, by a factor of 1413 for laptops. By the end of 2010 price per GB is less than 1/1300 of the price at the start of 1996.

Demand pull from firm size in disk drives and market size in personal computers; the organization of the industry; and technology push from exogenously growing stocks of knowledge contribute to quality improvement. Consistent with this the empirical analysis finds so far that firm size in disk drives and market size in personal computers (PCs), as well as technology push measured by stocks of patents in related technologies, firms, and industries are important factors in the rate of productivity improvement. The elasticity of capacity per disk with respect to firm disk drive sales ranges from 0.1 to 0.2; the elasticity with respect to PC shipments ranges from 0.25 to 0.4; and the elasticity with respect to the drive-related patent stock ranges from 1.6 to 2.9.

Other findings are that disk drives of firms that are soon to exit have lower capacity than drives of other firms. This supports the hypothesis that firms exit because they are unable to maintain the pace of productivity improvement as industry leaders. It also agrees with an alternative hypothesis, that firms who have decided to exit have less incentive to invest in productivity improvements than firms who plan to stay in the industry.

I. Introduction

In 1996 it required four years to complete a baccalaureate degree, but in an alternative universe suppose that students could graduate in 2½ days in 2010. Or imagine that within 14 years, train travel from Boston to Washington could be completed in one minute instead of seven hours. These advances equal the cumulative productivity increase—a factor of 375—that higher education and rail transport would have to deliver to match increases in disk drive capacity during the period 1995-2010.

In this paper I explore the forces that lie behind this rapidly improving performance. I attribute it to incentives to conduct research and development (R&D) provided by the organization of the industry, to demand pull coming from firm and market size, and to technology push from inventions in neighboring firms and industries. All of these interact with above average technological opportunity in the industry.

The relevant literature includes pioneering studies by Lerner (1995, 1997) of the disk drive industry. These papers find that pricing of drives declines in response to thin capitalization of adjacent rivals, and that firms which lag most behind industry leaders improve fastest, although not necessarily at a rate that achieves achieve parity with leaders or to survive in the industry.

A study by Aizcorbe and Kortum (2005) takes a vintage capital approach to cycles in CPU model introduction and retirement that is relevant to disk drives. It models the decision to replace capital equipment used to produce Central Processing Units (CPUs) given exogenous technological change in semiconductor manufacturing equipment. The model is in turn used to explain the CPU product cycle in pricing and in length of life. Klepper (1996) analyzes shakeouts and the evolution of innovative industries towards oligopoly and it has implications for exit decisions of disk drive companies.

Since disk drives have a strong “vertical” quality component, namely their storage capacity, Bresnahan (1987), which assumes vertical product differentiation, may be useful in study of cooperative and non-cooperative pricing. The paper finds that the price of an automobile model falls when neighboring models are priced competitively rather than collusively. This approach is generalized to models of product differentiation in Berry (1994), Berry, Pakes, and Levinsohn (1995), Nevo (2001), and Song (2007).

This paper is concerned with determinants of quality and price of disk drives where both are endogenous. The rate of technological progress in the industry is determined by firm and market size, by pricing pressure from rival firms, and finally by technology push: the supply of "outside" technologies that are useful to disk drive makers, but which are useful in many other industries.

The increase in storage capacity is a simple but comprehensive measure of technical improvement. It captures both process and product R&D because it simultaneously saves scarce materials and produces a higher quality product. In models of shakeouts (Klepper, 1996) firm size and quality of management determine survival in the face of pricing pressure. The disk drive industry has undergone a shakeout: during the period of analysis two-thirds of surviving firms exit. In addition to market size, progress in disk drives is determined partly through imitation (Mansfield, 1985), by technologies in related firms and industries worldwide, which exceed the boundaries of the disk drive industry. Finally, market size in the personal computer market controls expected growth in the demand for disk drives and this provides an additional inducement to undertake research in common with other research on market size and innovation (Acemoglu and Linn, 2004; Aghion and Howitt, 2009). The fact that the analysis includes mobile and desktop drives and personal computers provides a potentially identifying piece of information, since laptop PCs using 2.5" drives grow far faster than desktop drives using 3.5" drives. This effect is obscured by the miniaturization of laptops, which reduces the number of platters in portable drives.

Principal findings are first, that firm size in disk drive manufacturing is a significant determinant of the rate of technological progress, measured by storage capacity in Gigabytes (GB), the density of data storage, and price decline per GB of storage. Second, market size in personal computer shipments significantly influences the rate of progress in all three dimensions. Third, relevant patented technologies, which are largely exogenous, also govern improvements in disk drive performance, and it is important to take into account disk drive suppliers as well as disk drive makers. Finally, we find that firms which are about to exit the industry produce lower capacity drives, either because their imminent departure reduces incentives to imitate or because less innovative firms exit.

The rest of the paper consists of six sections. Section II describes the organization of the disk drive industry. It discusses the range of technologies that underpin its progress. Section III models the industry. It assumes that drive makers are non-cooperative Cournot-Nash rivals. However the firms are asymmetric in size, cost and productive efficiency and in the ability to do R&D. Thus firms differ in their ability to compete on quality. Roughly in line with the evidence, the model assumes that firm size is two-tiered: large firms have a greater incentive to conduct R&D than small firms, and because of this, they inherit unit costs in each period that are lower than those of small firms. The end result of the model is that in principle, firm and market size have identifiable and separate effects on R&D and the rate of progress. Again in principle, technology push from supplier firms inside and outside the industry has an additional and positive effect on the rate of progress in disk drive capacity. Section IV documents statistical trends in the industry, Section V describes the panel data constructed for this study, Section VI presents regression findings, and Section VII is a summary and outline of future research.

II. Description of the Disk Drive Industry

A. Industry Evolution

In this section I describe the industry, the nature of the product, and the sources of change in product performance. This discussion will enlarge the range of technologies seen as typically pertinent to drive drives, and it will extend the list of performers of the underlying research.

Hard disk drives were invented and commercialized by IBM in the mid 1950s as a mainframe peripheral. In accordance with well-known gains from specialization, the product has evolved into a separate industry that has experienced phenomenal growth. From a technical standpoint the density with which data are written to disk has doubled every three years. This has miniaturized the standard disk diameters known as form factors and it has increased storage capacity for a given form factor, sustaining miniaturize of personal computers and other devices requiring data storage. It is an important point that increases in areal density simultaneously improve product quality and save costs by economizing on materials. Research in the disk drive industry thus tends to be both product and process R&D. Moreover, process improvements that increase areal density also diversified the range of data storage products used in mainframes and mini-computers, personal computer desktops and laptops, and finally subnotebooks and digital audio players.

Disk drives conform to the life cycle of a new industry (Klepper, 1996; Klepper and Simons, 1997). Entry dominates at first, leading to growth in the number of firms, but eventually exit dominates, resulting in a decline in the number of firms, or a shakeout. For disk drives the number of firms peaked at almost 90 in 1984, afterwards declining to 20 as of 1997 (McKendrick, Doner, and Haggard, 2000). The shakeout has continued up to the present time. In 1996 there were nine disk drive makers; by 2009 this number had fallen to five; and by 2011 three remained[1]. Table 1 documents entry, mergers and acquisitions and exit for the industry during 1967-2011.

An important feature of the industry is that it includes suppliers of components, services and technologies besides disk drive makers. Suppliers are more numerous, not only those directly engaged in the supply of components, but also suppliers of ideas, and they are subject to different dynamics. The distinction is important: IBM continues to be a principal supplier of drive technologies despite its exit from production in 2003. Below I discuss how the supply of such technologies is disconnected from production by their applicability to other products.

The industry is increasingly dominated by Seagate and Western Digital, whose research groups and headquarters are in the US but whose production divisions are located in Singapore, Malaysia, and Thailand. The combination of cutting edge technology in North America and low-cost production in Southeast Asia has delivered an unbeatable combination of quality and price for the two firms (McKendrick, Doner, and Haggard, 2000).

[1] In 1996 the nine principal disk drive manufacturers were Fujitsu, Hitachi, IBM, Maxtor, Quantum, Samsung, Seagate, Toshiba, and Western Digital. By 2011 only Seagate, Toshiba, and Western Digital remained.

B. Disk Drive Technologies

Disk drives represent a convergence of technologies owing to complementarities between drive components and the rest of the computer. I summarize the diversity of components to show the range of technologies including their sophistication. I rely on this survey later on to justify selection of patent classes that describe the technologies, many of these practiced by firms that are neither drive makers nor suppliers of drive components.

The drive spindle holds platters to which data are written and from which read. The surface is a deposition of magnetic materials resistant to demagnetization. Deposition is performed on a nonmagnetic substrate, pitted at a microscopic level using sputtering techniques so as to bond to the magnetic layer. The magnetic layer is approximately 7×10^{-4} of the thickness of copying paper. In current models the layer consists of a cobalt-based alloy in turn coated by a layer of ruthenium. In turn the platters are sealed to the spindle by a magnetic fluid known as a ferrofluid. Ferrofluidic seals are superior to all known oil-based seals and holding the platters in a precise location relative to the read and write heads.

The heads are mounted on a small block known as a slider. It in turn is mounted on the actuator arm, which rides above the platters on an air cushion. The drive heads are in many ways the most remarkable components in disk drives since they have to be able to read and write data between two objects that move relative to one another, an area known as dynamic information storage and retrieval, and they must include error detection and correction mechanisms. The heads have experienced repeated, major advances. They were induced by increases in recording densities which trigger interactions between the heads and the disk surface. The write head magnetizes small regions in the thin film, and the read head plays back the recorded data. Besides the design of the heads, another major source of technical advance is in the magnetic recording technique. I return to the read-write heads below, when I consider the link between disk drives and fundamental science.

Disk drives have two electric motors. One operates the actuator while the other spins the platters. The motors have undergone numerous improvements to meet increasing demands for reliability and precision. Most important, Direct Current (DC) servo controlled motors operating at precise speeds with little vibration have replaced stepper motors.

Disk drives incorporate logic boards that contain memory and they include processors to control the heads, motors, read/write operations, and the internal cache memory that synchronizes the drive with the rest of the computer. So while disk drives are not semiconductors, the technology improves drive operation. Progress has also been made in improved interfaces and switches that connect the drive with the rest of the computer and enhance communication.

This survey has established the following classes of technologies as central to disk drives: advanced chemicals and materials, deposition of the materials, ferrofluidic and other magnetic seals, static and dynamic information storage and retrieval, error detection and correction, electric motors, semiconductors, communications, computer hardware and software, electrical devices. If the range of technologies comes as a surprise this is because disk drives consist of almost perfectly complementary components that rely on different branches of knowledge.

C. Links to Fundamental Science

The read and write heads of the drive are its most obvious link to recent fundamental science. The write head is an electromagnet that converts electrical into magnetic signals consisting of magnetic flux reversals written on the disk. It relies on the fact that applying an electric current to a coil produces a magnetic field. The direction of that field depends on the direction of the current. In older read heads, magnetic signals are converted into electrical ones by applying a magnetic field to a coil, causing an electric current to flow. Newer read heads do not use an induced electric current. It is here that the link to recent science becomes clear. Newer heads build on the principle of Magnetoresistance (MR), in which electrical resistance of a material changes subject to a magnetic field. A more recently discovered type of magnetoresistance is called Giant Magnetoresistance (GMR)[2].

GMR was discovered in the late 1980s: its discoverers were awarded the 2007 Nobel Prize in Physics. But this is not the most recent type of read head. It is based on Tunnel Magnetoresistance (TMR) in which electrons tunnel through a thin insulating barrier between ferromagnetic layers. TMR is used for read heads in the latest high density drives. The most science-intensive firm in disk drives, IBM, is responsible for successive introduction of read heads based on MR, GMR, and TMR principles as well as many other innovations in the industry over a long period.

GMR and TMR both entail polarization of the spin property of electrons. Spin is a two-state property with "up" or "down" states: it is a property of the electron distinct from its charge. Polarization here means dominance by one of the two states. The field of technology that relies on the spin property is known as spintronics (as in "spin transport electronics"). GMR and TMR read heads are among the first spintronic devices to be commercialized (Awschalom, Flatté, and Samarth, 2002).

The movement to more sophisticated read heads based on recent science is driven by the gain in capacity, miniaturization, and diversity of storage products that recording density allows. As density increases bits are more tightly packed on the surface. To get around magnetic interference, magnetic fields must be made weaker, requiring faster and more sensitive read/write heads.

III. Modeling the Industry

The following analysis assumes characteristics that are consistent with those of the disk drive industry. It builds on models of vintage capital in the microprocessor industry (Aizcorbe and Kortum, 2005), of vertical quality and pricing in differentiated products markets (Bresnahan, 1987), of shakeouts in oligopolies (Klepper, 1996), and the quality ladders model of economic growth (Barro and Sala-i-Martin, 2005).

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[2] Giant Magnetoresistance is observed in thin film structures in which ferromagnetic and non-magnetic layers alternate. The effect is defined as a significant change in electrical resistance depending on whether magnetization of adjacent ferromagnetic layers is parallel or anti-parallel.

Assumptions

Time is measured in discrete periods. Since product lines in the disk drive industry last about one year, one period corresponds to one year. I assume a vintage model for drive-making equipment, in which one unit of equipment produces one drive. However, more recent vintages of equipment produce higher quality drives, where quality is interchangeable with storage capacity. Earlier equipment vintages remain in use as long as their implicit rental price is at least equal to zero, meaning that the equipment saves cost and increases profit. Once rental price falls below zero a vintage of equipment is retired from service, as are the smaller storage capacity drives that they produce. Given rapid technological progress a given vintage of equipment lasts one period.

Vintages are partly firm-specific in that each firm i undertakes R&D r_{it} to replace the previous period's equipment. Replacement of last period's equipment increases quality of disk drives from $A_{i,t-1}$ to $A_{it}$for firm i with the amount of firm R&D determining the size of the step increase. The productivity of R&D is increased by licensed technology ℓ_t from suppliers who deal in many industries with other users of their technology. For this reason licensed technology can be viewed as growing exogenously with time. Licensed technology is a package deal that, in each period, costs a flat fee F_t.

Consumers are indifferent between one unit of quality A and A units of quality one so market demand is formulated in terms of capacity. Demand for disk drives is derived from the demand for personal computers. For simplicity let one computer utilize disk drives in a given fixed proportion. Therefore, growth in personal computers enables expansion of the market for disk drives.

Cost Conditions

Unit production cost for firm i at time t in natural units—disk drives not adjusted for capacity—is c_{it}. The implicit rental rate s_{it} of the latest drive-making equipment is the value of cost savings over the previous period's vintage. It is:

(1) $$s_{it} = \frac{c_{it}A_{it}}{A_{i,t-1}} - c_{it}$$

Since the latest equipment produces capacity in the ratio $A_{it}/A_{i,t-1} > 1$ at the same unit production cost as the previous vintage, (1) is the cost saving as well as the implicit rental rate. But combined unit cost is the implicit rental (1) plus unit production cost c_{it}. It is

$$(2) \qquad tc_{it} = \frac{c_{it}A_{it}}{A_{i,t-1}}$$

Equations (1) and (2) are measured in natural units of disk drives regardless of capacity (GB). So if total unit cost is measured instead per GB, it becomes

$$(3) \qquad \widetilde{tc}_{it} = \frac{c_{it}}{A_{i,t-1}}$$

Throughout a tilde indicates a variable measured per quality-adjusted unit.

Arbitrage Condition on Disk Drive Price

For firm i $\tilde{P}_{it}$ is the price of a disk drive per GB of storage capacity. Since in this analysis all quality differences are due to capacity differences, the fundamental arbitrage condition is that price per GB is the same across firms and models:

$$(4) \qquad \tilde{P}_{it} = \tilde{P}_{jt}$$

Since prices per effective and natural units are connected by the identity $\tilde{P}_{it} = P_{it}/A_{it}$ it follows that

$$(5) \qquad P_{it} = \frac{A_{it}}{A_{jt}} \cdot P_{jt}$$

The price of different units is higher or lower in proportion to capacity.

Market Demand

I assume a linear market inverse demand for disk drives expressed in quality-adjusted units. Price per GB declines as total capacity-weighted units $\tilde{Q}_t$ increase:

$$(6) \qquad \tilde{P}_t = a_t - b \cdot \tilde{Q}_t$$

In (6) total output of drives in capacity units is $\tilde{Q}_t = \tilde{q}_{it} + \tilde{q}_{2t} + \cdots + \tilde{q}_{nt}$ across n firms. Note that maximum price a_t grows with the demand for computers.

Firm Profit Function

The profit function for firm j is expressed in capacity units, since these are the units relevant for consumer demand. Using (3) and (6) this equals

$$\pi_{jt} = [a_t - b \cdot (\tilde{q}_{1t} + \tilde{q}_{2t} + \cdots + \tilde{q}_{nt})] \cdot \tilde{q}_{jt} - \widetilde{tc}_{jt} \cdot \tilde{q}_{jt} - F_t - r_{jt}. \tag{7}$$

Equation (7) is net profit: gross profit net of the flat package license fee (F_t) for licensed technology (ℓ_t) as well as the R& D expense of the firm (r_{jt}).

Cournot-Nash Market Structure

I begin with choice of the firm's output. I assume that firms license outside technology and I include the fixed fee F_t along with R&D r_{jt}. Firms engage in Cournot-Nash competition. They do not cooperate and each firm takes output of the others as given. This setup implies that within certain limits, inefficient firms coexist with efficient ones, as seems to be true during the industry's early years.

To capture size variation I assume a two-class structure with a few (n_L) large firms facing the same cost conditions and producing the same output[3]. In accordance with the size distributions of firms (ref.?) small firms are more numerous ($n_L > n_S$). I shall show that small firms have higher combined unit costs because, since they are smaller, they have less incentive to undertake R&D than large firms. Thus large firms have unit costs that are a fraction $\alpha, 0 < \alpha < 1$ of that of small firms: $\widetilde{tc}_{Lt} = \alpha \cdot \widetilde{tc}_{St}$.

Solving for Output and Price

The first order condition for any large firm (call it 1) occurs where marginal revenue equals marginal cost. It is

$$a_t - b \cdot \left(2\tilde{q}_{1t} + \tilde{q}_{2t} + \cdots + \tilde{q}_{n_L t} + \tilde{q}_{n_L+1,t} + \cdots + \tilde{q}_{nt}\right) = \alpha \cdot \widetilde{tc}_{St}$$

[3] This assumption can be readily generalized, for example to a uniform distribution for size and cost.

Using symmetry for large and small firms, this becomes

$$(8) \qquad a_t - b \cdot [(n_L + 1)\, \tilde{q}_{Lt} + n_S \tilde{q}_{St})] = \alpha \cdot \widetilde{tc}_{St}$$

The first order condition for any small firm (call it $n_L + 1$) is

$$a_t - b \cdot \left(\tilde{q}_{1t} + \tilde{q}_{2t} + \cdots + \tilde{q}_{n_L t} + 2\, \tilde{q}_{n_L+1,t} + \cdots + \tilde{q}_{nt}\right) = \alpha \cdot \widetilde{tc}_{St}$$

Again applying symmetry

$$(9) \qquad a_t - b \cdot [n_L \tilde{q}_{Lt} + (n_S + 1)\, \tilde{q}_{St})] = \widetilde{tc}_{St}$$

Solving (8) and (9) I find equilibrium output of large and small firms in every period:

$$(10) \qquad \begin{cases} \tilde{q}_{Lt}^{*} = \frac{a_t + [n_S - \alpha \cdot (n_S + 1)] \cdot \widetilde{tc}_{St}}{(n_L + n_S + 1) \cdot b} \\ \tilde{q}_{St}^{*} = \frac{a_t + [\alpha \cdot n_L - (n_L + 1)] \cdot \widetilde{tc}_{St}}{(n_L + n_S + 1) \cdot b} \end{cases}$$

Large firms are larger ($\tilde{q}_{Lt}^{*} > \tilde{q}_{St}^{*}$) if they are less numerous than small firms given their cost advantage. Industry output is $\tilde{Q}_t^{*} = n_L \tilde{q}_{Lt}^{*} + n_S \tilde{q}_{St}^{*}$. Inserting this in the demand function yields equilibrium price:

$$(11) \qquad \tilde{P}_t^{*} = \frac{a_t}{n_L + n_S + 1} + \frac{\alpha \cdot n_L + n_S}{n_L + n_S + 1} \cdot \widetilde{tc}_{St}$$

Price falls with exogenous technical change because $\widetilde{tc}_{st}$ declines, but ceteris paribus, it increases with growth in the PC market since a_t increases, and it increases because of a shakeout of small firms since the coefficients of a_t and $\widetilde{tc}_{st}$ increase. Thus, only if technology improves will price declines.

Licensed Technology and R&D

I assume that the flat price (F_t) of licensed technology is set low enough relative to the discrete profit gain from it that drive makers opt into the technology. Using this and the preceding relations I can now characterize the R&D decision.

Disk capacity is related to R&D and licensed technology through the following production function, specific to class j (large or small) firms:

(12) $$A_{jt} = B_{jt} \cdot r_{jt}^{\theta}$$

Returns to R&D are diminishing so $0 < \theta < 1$. In (12), B_{jt} depends on firm research productivity M_j and licensed technology ℓ_t as follows:

(13) $$B_{jt} = M_j \cdot (1 + \ell_t)^{\epsilon},$$

The term M_j captures ability to do R&D. Licensed technology is profitable when it raises profits by more than the license fee. The profit incentive transmits technology push that provides incentives to do R&D and improve disk capacity. Note that the effect of licensed technology ℓ_t diminishes if $0 < \varepsilon < 1$, so that technology push may weaken over time as ℓ_t grows.

Using (10)-(13) we reach the profit function for a class j firm:

(14) $$\pi_{jt}^{*} = \left(P_t^{*} - \widetilde{tc}_{jt}\right) \cdot \tilde{q}_{jt}^{*} - F_t - r_{jt}$$

Assume that (14) is at least equal to zero to make R&D meaningful. Next use the identity: $\tilde{q}_{jt}^{*} = A_{jt} q_{jt}^{*}$, where q_{jt}^{*} is the number of drives produced, and insert (12) in place of A_{jt} into (14),

(15) $$\pi_{jt}^{*} = \left(P_t^{*} - \widetilde{tc}_{jt}\right) \cdot B_{jt} \cdot r_{jt}^{\theta} \cdot q_{jt}^{*} - F_t - r_{jt}$$

Consider the optimized present value of firm$j$, in which output and R&D in future periods are set optimally:

(16) $$V_{jt} = \sum_{t=s}^{T_j} (1 + \rho)^{t-s} \pi_{js}^{*}$$

I compute the first order condition for R&D r_{jt}using (3) with subscripts advanced one period into the future to connect current R&D to future cost reductions. I obtain

(17) $$\frac{\partial \pi_{jt}^*}{\partial r_{jt}} = \left[\left(P_t^* - \widetilde{tc}_{jt}\right) \cdot q_{jt}^* + (1+\rho)^{-1} \cdot \widetilde{tc}_{j,t+1} \frac{A_{j,t+1}}{A_{jt}} \cdot q_{j,t+1}^*\right] \cdot \theta \cdot B_{jt} \cdot r_{jt}^{\theta-1} - 1 = 0$$

It may seem that the derivative must take account of the effects on future R&D expenditures. But if they are set optimally, the Envelope Theorem says that changes induced in future research by current research have no effect and must equal zero. Solving (17) for the equilibrium amount of R&D I reach:

(18) $$r_{jt}^* = \left\{\theta \cdot B_{jt} \cdot \left[\left(P_t^* - \widetilde{tc}_{jt}\right) \cdot q_{jt}^* + (1+\rho)^{-1} \cdot \widetilde{tc}_{j,t+1} \frac{A_{j,t+1}}{A_{jt}} \cdot q_{j,t+1}^*\right]\right\}^{\frac{1}{1-\theta}}$$

I can draw a number of conclusions using (18). In each case an increase in equilibrium R&D translates into increased product quality and firm size through (12) and (13). According to (18), equilibrium R&D increases with competency in R&D and with licensed technology as expressed in B_{jt}. Second, an increase in equilibrium disk drive price that corresponds to an expansion in the PC market (from (11), through an increase in a_t) increases R&D. Third, an increase in output because of a reduction in future unit cost increases equilibrium R&D. Therefore, movement of disk drive companies to Singapore in the 1980s to take advantage of lower costs of manufacture increased R&D effort in the U.S. and allowed these companies to pull ahead of others. Moreover, the relocation had option value, because it allowed firms to move easily to nearby Thailand and Malaysia to take advantage of lower costs as wages increased in Singapore relative to these countries (McKendrick, Doner, and Haggard, 2000).

Industry Evolution

It is easy to show that as time passes, large firms grow relative to small firms by doing more R&D. This drives down their combined unit cost more and improves the storage capacity of their disk drives more. The key relationships are (3) and (18). Suppose that total unit cost in (3) is equal across large and small firms in the initial period, because unit production cost and the inherited product quality are the same. Even so, an initial size advantage in (18) leads large firms to do more R&D, so that (3) begins to drop relative to the level in small firms with a growing quality advantage. And besides, this evolution is complementary with the stock of licensed technology. An advantage to large firms in R&D

efficiency will produce a similar result. Thus, despite the tolerance that the Cournot assumption holds for inefficient firms, eventually they will be forced out by pricing pressure from large firms. With these observations complete, let us turn to an empirical analysis of the disk drive industry.

IV. Industry Trends

A. Disk Drives

Figure 1 reports annual disk drive shipments during 1996-2010 (IDC, 2010) for 2.5" and 3.5" form factors. These are the dominant form factors for laptop and desktop computers and they are accordingly known as mobile and desktop drives[4]. To show differences in trend the data are normalized by their 1996 values. Mobile shipments grew 26 fold compared to growth of 3.5 times in desktop shipments, a result that is clearly determined by more rapid growth in laptop computers.

Table 2 reports drive units shipped, capacity per drive, and price per GB of storage (in 2005 $) at five year intervals by market segment, year, and drive diameter. As above the mobile segment grows faster than others, with the exception of drives with diameters 1.8" or less. These drives are typically used in mobile devices—cameras, cell phones, and audio players. After 2005 solid state drives start to replace disk drives in this segment.

The enterprise segment refers to drives designed for servers. The drives spin faster, serve data faster, and are more robust to failure. After 2005 enterprise drives begin to migrate from 3.5" to 2.5" diameters. Since they provide greater speed and reliability at the cost of storage, it is not surprising that enterprise drives are more costly and that their capacity is less than other segments.

Average storage capacity increases by 375 times in the desktop segment and by 236 in the mobile segment. The faster rate of improvement in the desktop segment is apparent and not real because of the miniaturization of laptop computers, which reduces the number of platters per drive. In fact, the price per GB in mobile drives relative to desktop drives actually falls, from 1.734 in 1996 to 1.600 in 2110. This suggests that the rate of technological progress is if anything more rapid in mobile drives.

[4] Figure 1 combines desktop drives with enterprise drives that are described below.

Table 2 shows that technical change in disk drives is both quality improving and cost-saving since the same materials store more data over time. For the remainder of this paper I concentrate on the desktop and mobile market segments. From the table these segments dominate the personal disk drive market.

B. Data on Personal Computers

Personal computer shipments largely determine demand for disk drives. Figure 2 shows trends in desktop and laptop shipments during 1995-2009 normalized by 1995 values. Desktops increase less than three times whereas laptops increase 20 times, so that the laptop market is larger by the end of the period. Since 2.5" drives are used in laptops and 3.5" drives are used in desktops, this differential rate of growth is a source of identification for this paper.

Table 3 contains additional details. For selected years it reports PC shipments, average CPU speed, and shares of 2-Core and 4-Core PCs. Improvements in instruction processing are likely to increase demand for data storage since processing speed and storage are complements in demand. And because the laptop market grows faster, given that market size is a driver of innovation, it becomes a more important determinant of technological change as specified by areal density, disk drive capacity in GBs, and price per GB.

C. Patent Statistics Relevant to Disk Drives

Section II part B surveyed components and technologies that comprise disk drives. It stressed the relevance of improvements in innovative materials and techniques. These include sputtering of the drive platter, etching of substrates, use of thin films and deposition methods, and improvements in recording techniques. Disk drives also must communicate with the rest of the computer and they must be capable of accurate data processing and file management, including error detection and correction. Even the core patent subcategory of information storage involves dynamic information retrieval and storage by the read/write heads, where information flows take place where one part moves relative to another, in addition to more familiar patent classes for memory devices and static information storage and retrieval. Disk drives must be measured and tested for flaws and Integrated Drive Electronics (IDE) includes semiconductor devices and circuitry that are similar to Central Processing units and memory devices used elsewhere in the computer. Finally, disk drives rely in a general way on electrical devices and power systems, as is shown by the importance of improvements in drive motors.

Table 4 lists a selection of NBER patent subcategories (Jaffe and Trajtenberg, 2002) that I have made based on the survey of disk drive components in Section II.B. I include eight subcategories: chemicals-miscellaneous; communications; computer hardware and software; information storage; electrical devices; measuring & testing; power systems; and semiconductors. The subcategories are broader and more inclusive than three-digit patent classes of the U.S. Patent and Trademark Office (USPTO) and I have chosen about five three-digit classes per subcategory, or 42 three-digit classes in total, that are plausibly relevant to technological change in disk drives based on the above survey. While I think of this set of technologies as relevant to disk drives, they are relevant as well to a wider range of applications: and to that extent they are exogenous with respect to size of the disk drive industry. For example, thin film technologies, signal and data processing, and even data storage have applications outside of the personal disk drive/personal computer industry.

To distinguish firms who are in the disk drive industry from others I identified 93 firms that are patent holders and members of IDEMA, the International Disk Drive Equipment and Materials Association (IDEMA, 2011)[5]. All major disk drive makers and most major component and technology suppliers in the industry belong to this Association.

For IDEMA patent holders Table 5 reports the distribution of patents by the eight subcategories in Table 4. The table reports distributions for all firms, disk drive makers except IBM, IBM alone, and disk drive component and technology suppliers. IBM is unique, not only in the scale of its patenting and in its

[5] IDEMA is not a research consortium, although a few IDEMA firms have recently begun joint research. In 2010 these formed the Advanced Storage Technology Consortium (ASTC) for the purpose of joint research into data recording techniques. Branstetter and Sakakibara (2001) analyze Japanese research consortia and draw conclusions for reasons why consortia succeed or fail to varying degrees.

contributions to the technology, but also in that it has been at various times both a drive maker and a component and technology supplier. Column 1 shows that patents in computer hardware and software, information storage, and semiconductor devices dominate. Together these subcategories account for ¾ of all patents. The picture changes slightly in Column 2, for disk drive makers. Information storage accounts for a larger share of patents by drive makers. Column 3 shows that computer hardware and software patents are more important for IBM.

Drive makers account for over half of patents issued in the industry and IBM accounts for another third. Thus in Column 4, drive suppliers account for one-sixth of patents[6]. Even so, suppliers contribute a larger proportion to chemicals-miscellaneous, measuring and testing, and power systems. These subcategories have to do with process technologies: treatment and preparation of the disk surface, thin film technology, measuring and testing of the finished surface, and provision of electric power. These are operations in which drive suppliers specialize.

Table 6 explores this specialization further by reporting the top 10 patent classes for the various classes: drive makers (except IBM), IBM, and drive suppliers. Patent counts are shown in parentheses. The table shows that patents of drive makers are dominated by information storage and semiconductors, with communications and other subcategories of secondary importance. The IBM patents are more uniformly distributed, but computer hardware and software are clearly more important relative to semiconductors and information storage. In the case of suppliers, semiconductors and information storage are also important, but for the first time, chemicals-miscellaneous and measuring and testing appear as important patent classes.

V. Panel Data on Disk Drives

I acquired panel data on worldwide shipments disk drives (IDC, 2010) and their characteristics from IDC, Framingham, Massachusetts, one of the world's leading providers of market intelligence on

[6] Nearly all patents granted to suppliers, about 15,200, are granted to publicly traded firms, compared with 300 patents granted to privately held suppliers. Since disk drive makers and IBM are all publicly traded, almost none of the patented inventions in the industry belong to private firms.

Information Technology. The data are quarterly and cover the period 1996Q1 through 2010Q4 for nine major disk drive makers: Fujitsu, Hitachi, IBM, Maxtor, Quantum, Samsung, Seagate, Toshiba, and Western Digital[7]. The data cover product classes by firm and quarter. Product classes are described by upper and lower limits on disk drive storage capacity in Gigabytes (GB), which reflect comprehensive surveys of a range of models produced by a firm in a given quarter. I replace upper and lower limits by the midpoint of capacity. The data also report mean storage capacity per disk or platter[8]. Revenues and units shipped when combined with capacity enable calculation of price per GB of storage. Price is indexed to 2005 using the implicit GDP deflator (**Survey of Current Business**, May 2011). While the product data are more aggregated than drive models, I shall refer to the data as product classes for the rest of the paper.

It is certainly true that capacity is not the only characteristic of a drive, as Lerner (1995) demonstrates in a hedonic analysis of drives based on detailed data from **Disk/Trend Reports** (James N. Porter, various years). However, it can be argued that capacity is the most important characteristic of a disk drive and that it is one to which other characteristics are tied. In any event, **Disk/Trend Reports** ceased publication in 1999.

Product classes typically last for one to two years before being replaced by higher capacity drives. Superimposed on this pattern is exit from product segments and the industry. The panel data in this study are therefore highly perforated. To take these patterns into account I have created measures of product entry, exit, and age, and of firm exit from product segments and the industry.

In addition to data on disk drives I acquired quarterly data from 1995 through 2009 on worldwide personal computer shipments (IDC, 2010), in order to capture market size effects on disk drive innovation. Included are more than 900 manufacturers of PCs. However, the top 10 firms account for

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[7] Four other disk drive makers appear in the data: Cornice, Excelstor, GS Magic, and Hewlett-Packard. However, their presence is fleeting. For a short while Excelstor produced 2.5 and 3.5 inch drives, and Hewlett-Packard exited at the start of the period. Cornice and GS Magic were transient producers of 1.0 inch drives used in hand-held digital devices, a segment that I do not consider in this paper.

[8] The number of disks per drive depends on the application. Mobile 2.5" drives have one to two disks, whereas desktop 3.5 inch drives can hold as many as seven. In some early models only one side of the disk is used for data storage, whereas both sides are covered by separate read-write heads in modern drives.

more than three-fourths of all shipments and the top 40 firms account for 93 percent. The nationality of PC makers can be determined, so that if any regional preference of PC makers for drive makers exists, it can be exploited. However, for all firms, the data report worldwide and not regional shipments.

The data include shipments, revenues, CPU speed, and the presence of two and four core processors, and they do so separately by mobile (laptop, notebook, and related) and desktop segments of the PC market. The CPU speed and multi-core indicators allow the construction of quality-adjusted PC shipments, which are "efficiency" measures of market size. The data do not account for miniaturization, a factor that impinges on disk drive performance, since there is an obvious tradeoff between miniaturization and drive capacity through drive height and the number of platters in a drive. For this reason I find it useful to include capacity per disk as a supplementary measure.

Besides data on disk drives and PCs I obtained panel data on patents by the subcategories shown in Table 4 for IDEMA firms who are patent holders and likely innovators in the industry. To do this I identified the headquarters of potential producers of advanced precision products used in disk drives, public/private ownership status, size, and founding dates. I used the IDEMA website and the websites of firms as a starting point, followed by an Internet search. This process yielded 126 firms in IDEMA that were likely patent holders. The roughly 300 other members of IDEMA were venture capital providers, startups with few employees, service companies, or had insufficient data. Assigning formal names to the 126 potential patent holders, I undertook a name match between target firms and names of assignees in the most current NBER patent database (National Bureau of Economic Research, 2010). This match identified 93 firms of which nine are drive makers. These could be linked to 858 patent assignees. Within the eight patent subcategories considered relevant to disk drives (see Table 4), these firms and assignees were awarded 93,127 patents during 1975 to 2006, the end date on the NBER data.

I intentionally specify a set of firms that goes beyond the major disk drive makers. As in many advanced industries (Von Hippel, 1988) suppliers of components and technologies play an important role. One would like to know what the contribution of all members of the industry are measured by patents held. Tables 4 to 6 in Section IV summarize these data collection efforts.

Using the assigned patent flows I accumulated quarterly patent stocks of the firms according to their grant date, dividing the stocks in turn according to the eight patent subcategories, and according to the patent assignees as linked to each of the disk drive makers and grouped accordingly; as well as to suppliers as a group, where for this purpose IBM is treated as a drive maker and not as a supplier. The patent stocks are accumulated using a quarterly depreciation and obsolescence rate of 0.0375, which corresponds to an annual rate of 0.15. Notice that I use quarterly patent stocks as measures of technology push that affect innovation, because the disk drive data and the PC shipments data are quarterly.

Table 7 reports key descriptive statistics for the panel. Panel A. reports hedonic measures of disk drives that represent product quality and performance. They have already been discussed: capacity per drive in GB, capacity per disk, and price per GB of storage in 2005 $. There are 7,434 firm-product class-quarterly observations dating from 1996Q1through 2010Q4. The average capacity is 163 GB, but this varies from 0.5 GB at the start of the period to 3.5 terabytes (TB) at the end. Capacity per disk is 82 GB; it is similarly wide-ranging, reflecting the highly trended nature of these statistics in the face of ongoing technological change. Finally price per GB (in 2005 $) is 20 $ but again this varies from 482 $ at the beginning of the period down to three cents at the end, underscoring the rapid improvement in the quality of disk drives during what a brief period of time.

Panel A. closes with measures of product and firm transience in the industry. Product age does this for transience of product classes, which average about one year. Firm exit does this for firms. It is an indicator variable equal to one if a given year and quarter is within two years of exit from the industry. Presumably, product age detracts from performance, since older products use fixed capital that produces lower capacity drives. Firm exit, measured as occurring with two years, seems likely to capture known departure of a firm, given that shutdown decisions take time. If this is so, then exit is likely to blunt incentives to improve disk drives. Alternatively, firms that are about to exit should sell lower quality drives. We explore this connection in the regression analysis.

Measures of market size (in 1000s of units) are found in Panel B. These are PC sales or shipments by PC form factor (desktop or laptop) and year-quarter; and sales of disk drives by market segment (desktop or mobile) and year-quarter. Taking out PCs produced by the same firm as an individual maker of disk drives as lacking in exogeneity, the rest of the PC industry sells a worldwide average of about 23 million units in a quarter and this increases with time as I have shown in the descriptive tables and figures. The number of matching firm-product class observations declines to 6,900 because the current PC shipment data end in Q4 of 2009. This costs all of the disk drive data for 2010. On the second line of Panel B., I report adjusted et of PC sales. This is PC sales weighted by CPU speed in GHZ. Both measures of rest of industry sales are expected to increase the incentives to improve drive performance, especially quality-adjusted PC sales, if CPU speed is complementary in demand with data storage. Panel B. closes with disk drive sales of the firm. If incentives to improve drives by drive makers are at least temporarily related to the size of their shipments, then this variable as well should be related to drive quality. It must be said, though, that it is not an easy task to devise an indicator of drive shipments that will not be highly collinear with PC shipments given the almost one-to-one relationship between these products in the markets for each taken as a whole.

Panel C. of Table 7 reports patent stocks in whole units. The NBER patent database ends in 2006. To obtain plausible instruments I have constructed patent stocks for all other drive makers and suppliers, besides the drive maker in question, and I have lagged the stocks by two years (eight quarters). The lag structure implies that the disk drive data for 2009 and 2010 are lost, so that 6,294 firm-product class observations remain of the original 7,434 observations, the necessary result of this instrumental variable strategy. On the first line of the panel I report the patent stock for disk storage alone, all other drive makers (including IBM when it is not the drive maker in question), and with a lag of two years. The stock is about 4,600 patents on average. On line two I enter the patent stock for other drive makers, in the dominant subcategories for firms in this industry of computer hardware and software, disk storage, and semiconductor devices. This is a stock of about 12,600 patents. When I consider the same stock for suppliers, this comes to about 2,000 patents, as before about one-sixth of the patents.

This completes the description of the panel. Let us now turn to regressions that seek to explain drive performance measured by capacity per drive, capacity per disk or platter, and price per GB of storage.

VI. Findings

This section reports simple fixed effect OLS panel regressions, where dummy indicators for firm and year are included in all equations, and where standard errors of the regression coefficients are robust and clustered by firms. Dependent variables in Tables 8, 9, and 10 respectively are: the logarithm of capacity per drive in GB, capacity in GB per disk, and price per GB in 2005 $. The first two are measures of product performance or quality, while as the third is an inverse measure of product performance whose decline increases consumers' surplus. For market size, a key driver of improvements in product quality, I use two primary indicators expressed in logarithms. They are: disk drive shipments of the firm and PC shipments. Note that PC shipments take out PC shipments, if any, of drive makers: they are shipments for the rest of the industry.

All equations include the logarithm of firm disk drive shipments. PC shipments consist of four alternative measures: shipments in natural units in the current period and two years' ahead and shipments weighted by CPU speed in the current period and two years' ahead. For this reason, in Tables 8-10 I enter the logarithm of PC market size indicators in a series of equations.

The second key driver of product quality is technology push. In order to create a more nearly exogenous measure it is an instrumental variable consisting of lagged patent stocks of other makers of disk drives and suppliers of drive components. But I find that patent stocks that include the top three patent subcategories of: computer hardware and software, disk storage, and semiconductor devices outperform patent stocks for disk storage alone. This is despite the fact that disk storage patent stocks also perform well. For this reason the tables limit reporting to more inclusive patent stocks.

Table 8 contains results where the dependent variable is the logarithm of capacity per drive. All market size variables contribute to increased drive capacity and usually with significance. In this assessment, and for the rest of the paper, I hold time and drive maker constant, so the measured effect relies on within year and firm variation. The elasticity of capacity per drive with respect to disk drive sales ranges from 0.07 to 0.20. PC market size does a little better. Over the different measures, the elasticity of capacity per drive with respect to varies from 0.18-0.40. Better results are obtained for PC shipments adjusted for CPU speed, suggesting that processing power is complementary to disk storage and to innovation in it.

Patent stocks for the rest of the industry also contribute to capacity per drive, sometimes with statistical significance. Point estimates are large compared with market size but exhibit wide variation: elasticities of drive capacity with respect to the patent stocks range from 0.4 to 1.8.

Product age, measured in years since a product class was introduced, is associated with a significant drop in capacity. The effect is precisely estimated and an increase in product age of one year lowers the logarithm of price by 0.38. Firm exit within the next two years is linked to a drop in capacity, not always with significance. This is consistent either with the hypothesis that exit reduces incentives to improve drive capacity or with the hypothesis that firms selling lower capacity drives are the ones that will exit.

In Table 9 the dependent variable is the logarithm of storage capacity in GB per disk. Compared to storage capacity per drive, this measure holds the number of platters constant, since Capacity per Drive=Capacity per Disk × Disks per Drive. Capacity per disk is more closely related to areal density. And since miniaturization of laptop PCs reduces the number of disks per drive, disk capacity results in a downward bias in the effects of market size and technology push compared with capacity per disk.

Compared with Table 8, coefficients of market size are slightly higher, suggesting that market size encourages some degree of miniaturization as well as areal density. Otherwise effects on capacity per drive would equal those on capacity per disk. But the effect of the patent stocks changes much more. The patent stock elasticities increase by 50-100 percent compared to Table 8, and vary from 1.6-2.9. More than was the case for market size this suggests that technology push contributes to miniaturization and to a decline in disks per drive as well as to an increase in recording density.

Product age and firm exit are linked to reduced capacity per disk. As before firm exit is associated with lower performance. Again this is because firms that are about to exit reduce the improvement in drive density or because firms who sell lower density drives must exit.

In Table 10 the dependent variable is the logarithm of the deflated price per gigabyte (GB). Given that market size and technology push increase density of storage and also contribute to miniaturization and materials saving, both factors should contribute to price reductions per unit of storage.

This is what the regressions find. Market size encourages research in materials saving and to price reductions per unit of storage. The same is true of technology push: patent stocks contribute to significant price reductions. Indeed the coefficients are nearly the opposite of those in Table 9, because increases in areal density correspond to decreases in materials cost. This emphasizes that technological progress in disk drive technology simultaneously improves product quality and lowers cost of production.

Product age is linked to a higher price per unit of storage, and the coefficients are statistically highly significant. This finding is consistent with exit from older product classes as consumers turn to higher storage drives. Storage per drive rises, so that older drives are marked down even though they are more costly in the materials used, which again contributes to product replacement. Firm exit has no effect on price per unit of storage, because of arbitrage conditions on price. Compare this to Table 9 where firm exit is linked to lower capacity per disk. Putting these results together, Table 9 and Table 10 show that the price per disk is lower in firms that are about to leave the industry, in proportion to the lower density of the drives produced by these firms. This again is consistent with price arbitrage.

Table 11 studies the feasibility of simple localized measures of market size and technology push. All three product performance measures are dependent variables. Market size consists of PC sales of other firms in the same hemisphere (east, west) and technology push consists of patent stocks of other firms in the disk drive industry but in the same hemisphere. In these “hemispheric” regressions, since some errors in the right hand side variables are being introduced, it is to be expected that estimated coefficients would be biased towards zero, even though most are significantly different from zero. The key point is that the table confirms the relevance of worldwide PC market size and technology push over simple regional measures.

The combined thrust of the empirical work on disk drives is that both market size (disk drive sales; PC sales) and technology push (patent stocks external to a disk drive maker) contribute to improvements in capacity, and necessarily, price decreases per GB of storage.

VII. Conclusion

In this paper I have documented the remarkable improvements in disk drive storage capacity in recent decades, an important determinant of the functionality of personal computers; and I have explored both theoretically and empirically the causal factors underling the improvements in product quality. Since these findings are reasonably clear from the preceding exposition, in these final paragraphs I would like to discuss future improvements to the research design.

To begin with, the measures of PC market size that I currently use could in principle be improved on by being made more specific to firms. To date, I use mostly global market size for disk drive shipments of the company in a given market segment (desktop or mobile) and for personal computer shipments in the same segment but in the rest of the industry. The use of global measures is likely to increase the correlation between firm level sales of disk drives and market sales of PCs, when perhaps their effects could be more easily identified.

Along similar lines, in some cases disk drive makers may sell regionally and not globally to PC makers. This could be explained by transportation costs and perhaps local consumer preferences. One way in which to change the current specification of PC market size is to assume that there is a home country advantage in personal computer sales. Thus, increased cross-sectional variation could be introduced in the market size indicator for personal computers by replacing global market sales with a measure centered on the same country as the disk drive maker, but not necessarily limited to that country. However, in either case the key challenge is whether contractual measures of linkage between disk drives and PCs are available, the answer to which is unclear at present.

To assume that all sales of disk drives by individual drive makers in a given market segment provide equal incentives to do research may be too strong an assumption. It may be that sales within firms that produce both disk drives and personal computers provide a stronger incentive, owing to the infra-marginal gains from transfer pricing, under conditions of rising marginal cost. The error could also lie in the opposite direction: disk drive performance in either desktop or mobile segments could be determined by the combined market across segments and not within separate segments.

The patent stocks that serve as measures of technology push in this paper may be too aggregative and too restricted to drive industry. Work by Keller (2002) and Peri (2005) indicates that knowledge flows erode with distance, language, and political boundaries, consistent with localized networks of scientists and inventors (Singh, 2005). Using their measures of erosion in knowledge flows, firm-specific measures of technology push in the form of localized patent stocks could be readily constructed. These stocks could in turn be instrumented using lagged stocks of other firms and firms outside of the industry, but inside the same geographic orbit.

Additional work that could be done includes exploration of the dynamics of market shares, including exit. The prospects for building on, improving, and extending the current results appear to be bright.

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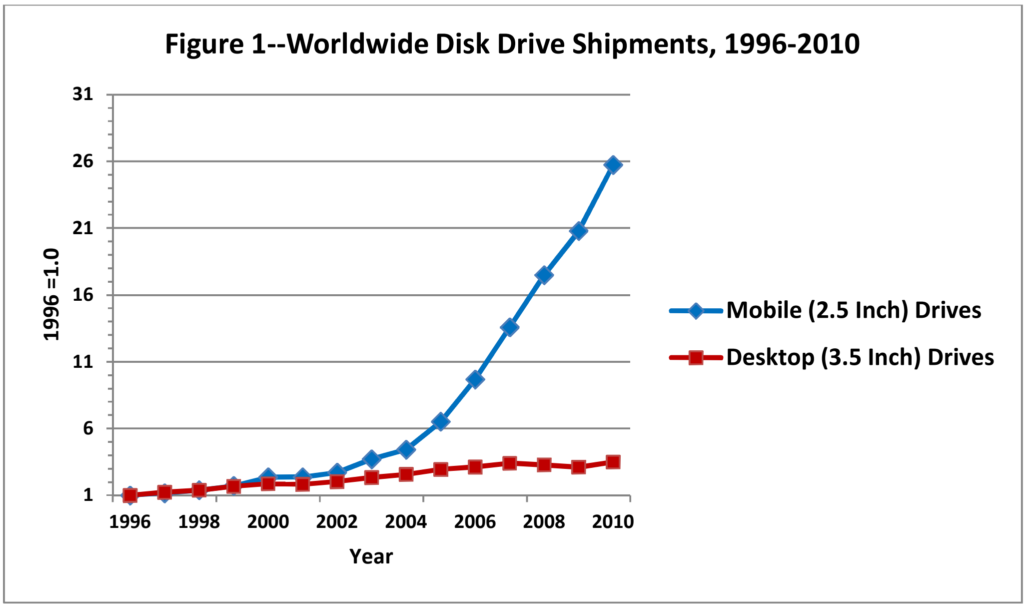
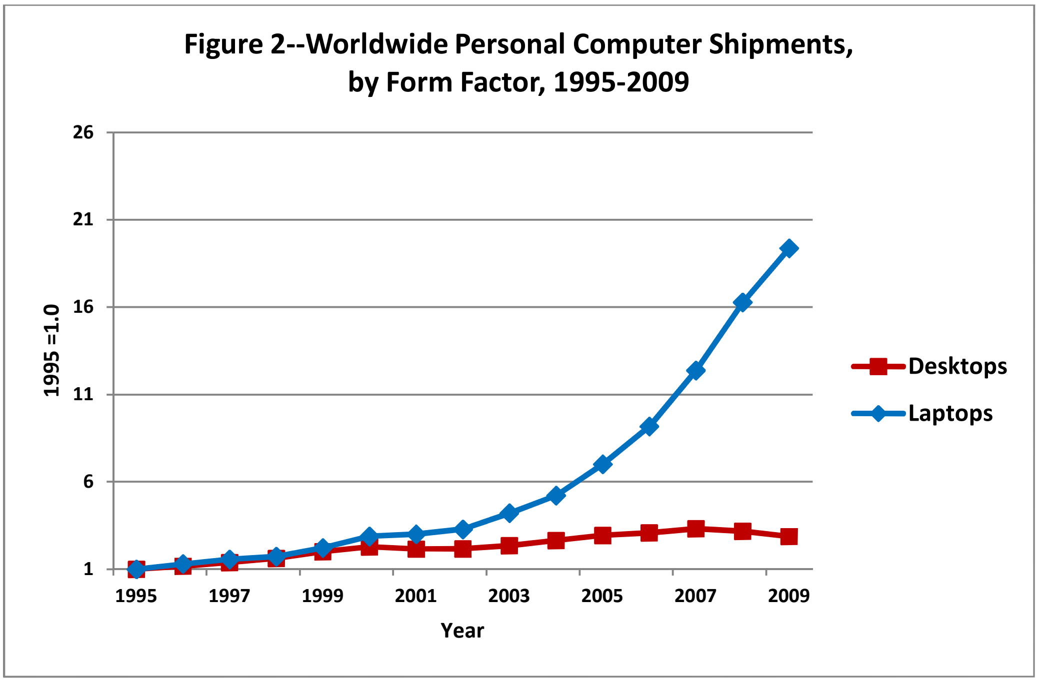
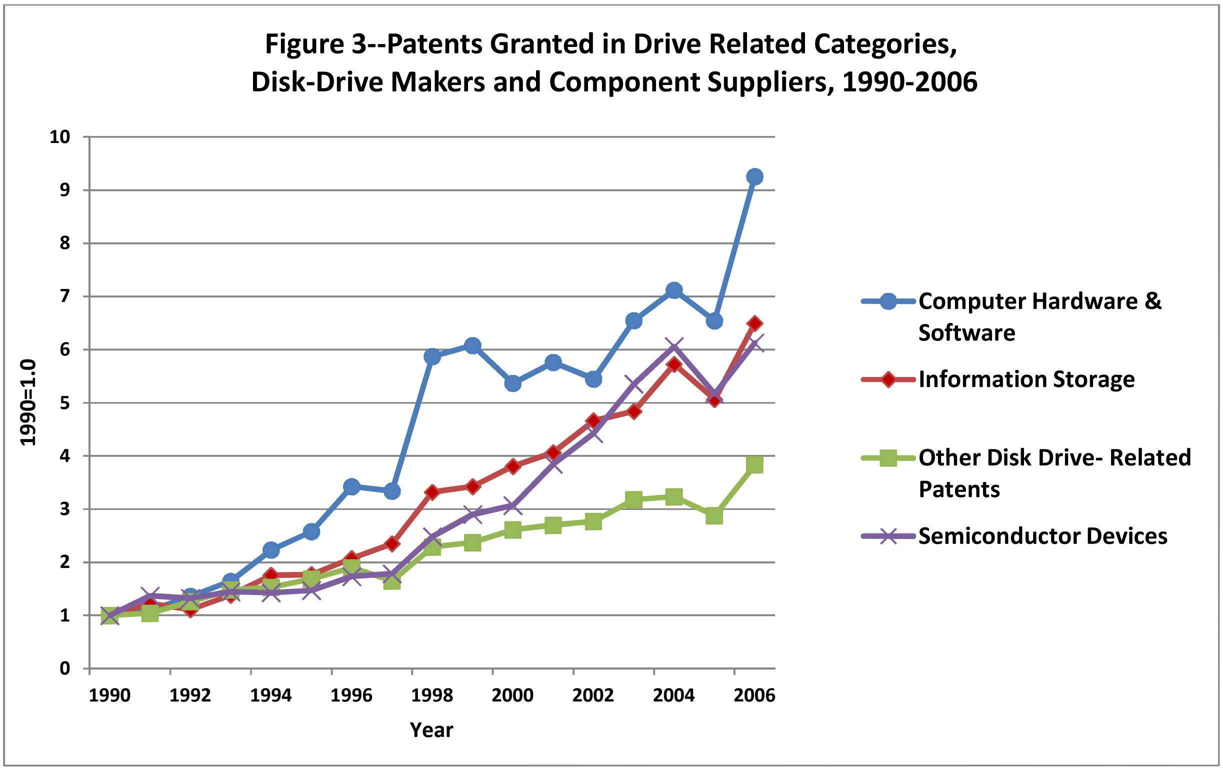


Source: IDC, **Worldwide Quarterly Hard Disk Drive Shipments and Revenues**, November 2010



Source: IDC, **Worldwide Quarterly PC Tracker**, November 2010



Source: NBER, **Patent Data Project PDP Database**, August 2010

Table 1
Entry, Exit and Consolidation in the Disk Drive Industry, 1967-2011

1967	Hitachi and Toshiba enter
1979	Seagate Technology Founded
1988	Western Digital enters acquisition of Tandon's disk division
1988	Samsung enters
1989	Seagate acquires Control Data Corporation's disk division: CDC exits
1990	Maxtor purchases Miniscribe's disk division out of bankruptcy
1994	Quantum purchases DEC's disk division: DEC exits
1996	Seagate acquires Conner Peripherals: Connor exits
2000	Maxtor acquires Quantum: Quantum exits
2003	Hitachi acquires IBM's disk division, forming Hitachi Global Storage Technologies (HGST): IBM exits
2006	Seagate acquires Maxtor: Maxtor exits
2009	Toshiba acquires Fujitsu's disk division: Fujitsu exits
2011	Western Digital acquires Hitachi's disk division (HGST): Hitachi exits
2011	Seagate acquires Samsung's disk division: Samsung exits

Source: Wikipedia.

Table 2
Worldwide Disk Drives Shipped, Average Capacity, and Unit Price per GB
1996-2010

Market Segment	Year*	Drive Diameter	Units Shipped (1000s)	Average Capacity (GB)	Unit Price Per GB (2005 $/GB)
Desktop [a]					
	1996	3.5"	18,385	1.633	$130.35
	2000	3.5"	36,785	14.144	$9.02
	2005	3.5"	57,912	113.176	$0.64
	2010	3.5"	77,212	613.074	$0.10
Mobile [b]					
	1996	≤1.8"	n. a.	n. a.	n. a.
	2000	≤1.8"	25	0.500	$525.45
	2005	≤1.8"	7,610	18.803	$12.55
	2010	≤1.8"	1,680	144.594	$0.40
	1996	2.5"	2,695	1.412	$226.06
	2000	2.5"	7,225	9.525	$18.12
	2005	2.5"	16,874	62.730	$1.30
	2010	2.5"	75,702	333.263	$0.16
Enterprise [c]					
	1996	3.5"	2,829	3.424	$226.96
	2000	3.5"	4,506	14.483	$29.72
	2005	3.5"	6,270	92.474	$2.46
	2010	3.5"	4,305	343.913	$0.53
	1996	2.5"	n. a.	n. a.	n. a.
	2000	2.5"	n. a.	n. a.	n. a.
	2005	2.5"	65	53.796	$3.28
	2010	2.5"	3,267	198.665	$0.65

Notes: Source: IDC, **Worldwide Quarterly Hard Disk Drive Shipments and Revenues**, November 2010. * Data are taken from first quarters of each year. [b] Mobile segment includes portable devices as well as laptops. [c] Enterprise segment refers to disk drives designed for multi-user computers. Drives in this segment spin more rapidly, are more robust to failure, and use smaller platters to limit air resistance, because reliability and speed are more important than capacity.

Table 3
Worldwide Personal Computers Shipped, Average CPU Speed, and Share of Multi-core CPUs, 1996-2010

Market Segment	Year*	Units Shipped (1000s)	Average CPU Speed (MHZ)	Share of Two-Core PCs	Share of Four-Core PCs
Desktop PCs					
	1995	10,643	75.01	n. a.	n. a.
	2000	25,360	627.19	n. a.	n. a.
	2005	32,045	2,824.30	0.00	n. a.
	2009	31,826	2,488.77	0.74	0.09
Laptop PCs					
	1995	2,056	75.00	n. a.	n. a.
	2000	5,802	490.72	n. a.	n. a.
	2005	12,919	1,938.16	n. a.	n. a.
	2009	33,944	2,200.44	0.74	0.00

Source: IDC, **Worldwide PC Tracker**, November 2010. * Data are taken from first quarter of each year.

Table 4
U.S. Patent and Trademark Office Patent Classes
Relevant to Disk Drive Manufacturing

Subcategory, Patent Class Title	Patent Class
A. Chemicals—Miscellaneous (NBER Patent Subcategory 19)	
Metal Treatment	148
Adhesive Bonding and Miscellaneous Chemical Manufacture	156
Chemistry: Electrical and Wave Energy	204
Electrolysis: Processes, Compositions Used Therein, and Methods of Preparing the Compositions	205
Etching a Substrate: Processes	216
B. Communications (NBER Patent Subcategory 21)	
Communications: Electrical	340
Multiplex Communications	370
Pulse or Digital Communications	375
C. Computer Hardware & Software (NBER Patent Subcategory 22)	
Coded Data Generation or Conversion	341
Data Processing: Generic Control Systems or Specific Applications	700
Data Processing: Database & File Management or File Structures	707
Electrical Computers & Digital Processing Systems: Multi-Computer Data Processing	709
Electrical Computers & Digital Processing Systems: Input/Output	710
Electrical Computers & Digital Processing Systems: Processing Architectures & Instruction Processing	712
Electrical Systems: Support	713
Error Detection/Correction & Fault Detection/Correction	714
Data Processing: Software Development, Installation, and Management	717
D. Information Storage (NBER Patent Subcategory 24)	
Dynamic Magnetic Information Storage or Retrieval	360
Static Information Storage & Retrieval	365
Dynamic Information Storage or Retrieval	369
Electrical Computers and Digital Processing Systems: Memory	711
Dynamic Optical Information Storage or Retrieval	720
E. Electrical Devices (NBER Patent Subcategory 41)	
Demodulators	329
Amplifiers	330
Oscillators	331
Modulators	332
Electricity: Magnetically Operated Switches, Magnets, Electromagnets	335
Inductor Devices	336
Electric, Electro-thermal, and Thermally Activated Switches	337

Table 4
U.S. Patent and Trademark Office Patent Classes
Relevant to Disk Drive Manufacturing

Subcategory, Patent Class Title	Patent Class
F. Measuring & Testing (NBER Patent Subcategory 43)	
Measuring & Testing	73
Electricity: Measuring & Testing	324
Optics: Measuring & Testing	356
Thermal Measuring & Testing	374
Scanning-Probe Techniques or Apparatus: Applications of Scanning-Probe Techniques	850
G. Power Systems (NBER Patent Subcategory 45)	
Electrical Generator or Motor Structure	310
Electricity: Motive Power Systems	318
Electrical Systems & Devices	361
Electricity: Motor Control Systems	388
H. Semiconductor Devices (NBER Patent Subcategory 46)	
Active Solid-State Devices (Transistors and Solid-State Diodes)	257
Electronic Digital Logic Circuitry	326
Semiconductor Manufacturing Process	438
Data Processing: Design and Analysis of Circuit or Semiconductor	716

Source: NBER, **Patent Data Project PDP Database**, August 2010.

Table 5
Distribution of Patents by Subcategories
Disk Drive Companies

Subcategories (NBER Number)	All Firms	Disk Drive Makers, Excluding IBM	IBM	Disk Drive Suppliers, Excluding IBM
Chemicals-Miscellaneous (19)	3,727 (4.00%)	1,445 (2.91%)	981 (3.51%)	1,301 (8.36%)
Communications (21)	7,126 (7.65%)	4,453 (8.97%)	1,743 (6.24%)	930 (5.98%)
Computer Hardware and Software (22)	20,491 (22.00%)	7,621 (15.36%)	11,259 (40.29%)	1,611 (10.36%)
Electrical Devices (41)	2,047 (2.2%)	1,128 (2.27%)	292 (1.04%)	627 (4.03%)
Information Storage (24)	26,138 (28.07%)	16,583 (33.41%)	5,658 (20.25%)	3,897 (25.06%)
Measuring and Testing (43)	5,151 (5.53%)	2,626 (5.29%)	978 (3.50%)	1,547 (9.95%)
Power Systems (45)	5,534 (5.94%)	3,243 (6.53%)	1,056 (3.78%)	1,235 (7.94%)
Semiconductor Devices (46)	22,913 (24.60%)	12,532 (25.25%)	5,976 (21.4%)	4,405 (28.3%)
Total	93,127 (100.00%)	49,631 (100.00%)	27,943 (100.00%)	15,553 (100.00%)

Notes: Source: author's calculations and NBER, **Patent Data Project PDP Database**, August 2010. Time period is 1975 through 2006. All firms are members of IDEMA, the International Disk Drive Equipment and Materials Association. Terms in parentheses are column percentages that sum to 100% except for rounding error. See Table 4 for the three-digit patent classes under each subcategory that were extracted for purposes of this study.

Table 6
Leading Patent Classes, Disk Drive Companies

Patent Class: Class Title (Number of Patents)		
Disk Drive Makers, Excluding IBM	IBM	Disk Drive Suppliers, Excluding IBM
1. Class 360: Dynamic Magnetic Information Storage or Retrieval (6,385)	1. Class 438: Semiconductor Manufacturing Process (2,694)	1. Class 257: Active Solid-State Devices (Transistors and Solid-State Diodes) (2,014)
2. Class 257: Active Solid-State Devices (Transistors and Solid-State Diodes) (6,231)	2. Class 707: Data Processing: Database & File Management or Data Structures (2,607)	2. Class 360: Dynamic Magnetic Information Storage or Retrieval (1,745)
3. Class 365: Static Information Storage & Retrieval (5,623)	3. Class 711: Electrical Computers and Digital Processing Systems: Memory (2,232)	3. Class 438: Semiconductor Manufacturing Process (1,744)
4. Class 438: Semiconductor Manufacturing Process (4,846)	4. Class 257: Active Solid-State Devices (Transistors and Solid-State Diodes) (2,088)	4. Class 365: Static Information Storage & Retrieval (915)
5. Class 370: Multiplex Communications (2,527)	5. Class 360: Dynamic Magnetic Information Storage or Retrieval (1,961)	5. Class 369: Dynamic Information Storage or Retrieval (780)
6. Class 369: Dynamic Information Storage or Retrieval (2,429)	6. Class 709: Electrical Computers and Digital Processing Systems: Multi-Computer Data Processing (1,935)	6. Class 361: Electrical Systems & Devices (724)
7. Class 711: Electrical Computers and Digital Processing Systems: Memory (1,785)	7. Class 714: Error Detection/Correction and Fault Detection/Recovery (1,832)	7. Class 156: Adhesive Bonding and Miscellaneous Chemical Manufacture (559)
8. Class 714: Error Detection/Correction and Fault Detection/Recovery (1,756)	8. Class 710: Electrical Computers and Digital Processing Systems: Input/Output (1,527)	8. Class 324: Electricity Measuring & Testing (539)
9. Class 361: Electrical Systems & Devices (1,522)	9. Class 365: Static Information Storage & Retrieval (1,100)	9. Class 356: Optics: Measuring & Testing (530)
10. Class 375: Pulse or Digital Communications (1.411)	10. Class 370: Multiplex Communications (1,047)	10. Class 716: Data Processing: Design and Analysis of Circuit or Semiconductor Mask

Source: author's calculations and NBER, **Patent Data Project PDP Database**, August 2010. All firms are members of IDEMA, the International Disk Drive Equipment and Materials Association. The 10 patent classes in each column account for 69.54%, 68.08%, and 64.69% of patents respectively, for the 42 disk drive-related patent classes shown in Table 4.

Table 7
Descriptive Statistics, Principal Variables in the Disk Drive Panel

Variables	Obs.	Mean	Std. Dev.	Min	Max
Panel A. Drives and Drive Makers					
Capacity per Drive (GB/Unit)	7,434	162.56	304.35	0.5	3,495
Capacity per Disk (GB/Disk)	"	82.14	115.85	0.11	750
Price per GB (in 2005 $)	"	20.00	43.41	0.03	482.42
Product Age (in Years)	"	1.09	1.10	0	8.25
Firm Exits Within Two Years (1 if yes, 0 if no)	"	0.11	0.31	0	1
Panel B. Market Size (1000s)					
Current Rest of Industry PC Sales	6,900	23,482.34	11,637.37	1,865.12	52,500.58
Adjusted Current Rest of Industry PC Sales, Weighted by CPU Speed in GHZ	"	40,779.89	37,003.26	139.89	114,000.60
Firm Disk Drive Sales	7,434	8,408.41	7,499.34	0.5	34,645.00
Panel C. Technology Indicators (Whole Units)					
Patent Stock in Subcategory Disk Storage, Other Drive Makers [a]	6,294	4,623.14	1,979.65	1,443.69	8,509.57
Patent Stock in Top Three Patent Subcategories, Other Drive Makers [b]	"	12,592.12	5,767.74	4,000.89	23,771.35
Patent Stock in Top Three Patent Subcategories, Suppliers [b]	"	2,069.61	1,476.86	627.47	5,118.99

Notes: Period is year 1996 quarter 1 through year 2007 quarter 4. Patent stocks are depreciated at a quarterly rate of 0.0375. [a] Disk storage is patent subcategory 24. [b] Top three patent subcategories are: computer hardware and software (22), disk storage (24), and semiconductor devices (46). See Table 4 of the text for additional explanation.

Table 8—Determinants of Capacity Per Drive (in GB/unit)
(Robust, Clustered Standard Errors in Parentheses)

Variable or Statistic	Dependent Variable: Log (Capacity per Drive)				
	Eq. 8.1	Eq. 8.2	Eq. 8.3	Eq. 8.4	Eq. 8.5
Firm, Year Dummies Significant?	Included Yes	Included Yes	Included Yes	Included Yes	Included Yes
Log (Firm Disk Drive Sales)	0.204 (0.048)	0.112* (0.065)	0.068* (0.051)	0.167 (0.067)	0.141 (0.058)
Log(Rest of Industry Current PC Sales)		0.305 (0.101)			
Log(Rest of Industry Current PC Sales, Weighted by Processor Speed)			0.396 (0.079)		
Log(Rest of Industry PC Sales, Two Years' Ahead)				0.177* (0.168)	
Log(Rest of Industry PC Sales, Two Years' Ahead, Weighted by Processor Speed)					0.246 (0.118)
Log (Other Drive Makers' and Suppliers' Patent Stocks, Top Three Patent Subcategories)	1.825 (0.301)	1.008* (0.539)	0.405* (0.545)	1.679 (0.548)	1.235 (0.566)
Product Age (in fractional years)	-0.373 (0.017)	-0.371 (0.018)	-0.373 (0.019)	-0.387 (0.022)	-0.387 (0.022)
Firm Exit Within the Next Two Years (1 if yes, 0 if no)	-0.128* (0.068)	-0.170 (0.080)	-0.192 (0.074)	-0.126* (0.082)	-0.150 (0.084)
Number of Observations	6,294	6,294	6,294	5,524	5,524
R^2	0.881	0.886	0.890	0.880	0.882
Root Mean Squared Error	0.598	0.586	0.574	0.576	0.571

Notes: Capacity per drive is the midpoint between the upper and lower limits for each product class.
* Coefficient is ***not*** significant at the five percent level of significance.

Table 9—Determinants of Capacity per Disk (in GB/platter)
(Robust, Clustered Standard Errors in Parentheses)

Variable or Statistic	Dependent Variable: Log (GB per Disk)				
	Eq. 9.1	Eq. 9.2	Eq. 9.3	Eq. 9.4	Eq. 9.5
Firm, Year Dummies Significant?	Included Yes	Included Yes	Included Yes	Included Yes	Included Yes
Log (Firm Disk Drive Sales)	0.215 (0.035)	0.115 (0.040)	0.086 (0.029)	0.161 (0.045)	0.137 (0.037)
Log(Rest of Industry Current PC Sales)		0.332 (0.047)			
Log(Rest of Industry Current PC Sales Weighted by Processor Speed)			0.378 (0.036)		
Log(Rest of Industry PC Sales, Two Years' Ahead)				0.252 (0.095)	
Log(Rest of Industry Adjusted PC Sales, Two Years' Ahead, Weighted by Processor Speed)					0.299 (0.054)
Log (Other Drive Makers' and Suppliers' Patent Stocks, Top Three Patent Subcategories)	2.934 (0.205)	2.045 (0.350)	1.579 (0.324)	2.461 (0.291)	2.019 (0.276)
Product Age (in fractional years)	-0.312 (0.013)	-0.310 (0.014)	-0.312 (0.014)	-0.323 (0.021)	-0.324 (0.021)
Firm Exit Within the Next Two Years (1 if yes, 0 if no)	-0.157 (0.061)	-0.203 (0.061)	-0.218 (0.055)	-0.151 (0.054)	-0.175 (0.054)
Number of Observations	6,294	6,294	6,294	5,524	5,524
R^2	0.969	0.974	0.976	0.970	0.972
Root Mean Squared Error	0.328	0.303	0.288	0.312	0.302

Notes: GB per disk is the average capacity per disk or platter, for each product class.

Table 10—Determinants of Price per Unit of Storage (in 2005 $/GB)
(Robust, Clustered Standard Errors in Parentheses)

Variable or Statistic	Dependent Variable: Log (Price per GB)				
	Eq. 10.1	Eq. 10.2	Eq. 10.3	Eq. 10.4	Eq. 10.5
Firm, Year Dummies	Included	Included	Included	Included	Included
Significant?	Yes	Yes	Yes	Yes	Yes
Log (Firm Disk Drive Sales)	-0.215	-0.094*	-0.053*	-0.153	-0.122
	(0.043)	(0.057)	(0.048)	(0.059)	(0.049)
Log(Rest of Industry Current PC Sales)		-0.401			
		(0.092)			
Log(Rest of Industry Current PC Sales Weighted by Processor Speed)			-0.472		
			(0.072)		
Log(Rest of Industry PC Sales, Two Years' Ahead)				-0.282*	
				(0.151)	
Log(Rest of Industry PC Sales, Two Years' Ahead, Weighted by Processor Speed)					-0.354
					(0.101)
Log (Other Drive Makers' and Suppliers' Patent Stocks, Top Three Patent Subcategories)	-2.882	-1.807	-1.188	-2.266	-1.696
	(0.279)	(0.537)	(0.501)	(0.525)	(0.526)
Product Age (in fractional years)	0.201	0.199	0.201	0.188	0.188
	(0.018)	(0.017)	(0.016)	(0.024)	(0.025)
Firm Exit Within the Next Two Years (1 if yes, 0 if no)	-0.038*	0.018*	0.039*	-0.070*	-0.040*
	(0.075)	(0.074)	(0.062)	(0.062)	(0.062)
Number of Observations	6,294	6,294	6,294	5,524	5,524
R^2	0.957	0.963	0.966	0.958	0.961
Root Mean Squared Error	0.439	0.410	0.391	0.411	0.399

Notes: Price per GB is the deflated average price (in 2005$) per unit of storage expressed in GB.
* Coefficient is ***not*** significant at the five percent level of significance.

Table 11—Hemispheric Specifications, Disk Drive Performance
(Robust, Clustered Standard Errors in Parentheses)

Variable or Statistic	Dependent Variables:					
	Log (Capacity per Drive)		Log (GB per Disk)		Log (Price per GB)	
	Eq. 11.1	Eq. 11.2	Eq. 11.3	Eq. 11.4	Eq. 11.5	Eq. 11.6
Firm, Year Dummies Significant?	Included Yes	Included Yes	Included Yes	Included Yes	Included Yes	Included Yes
Log (Firm Disk Drive Sales)	0.162 (0.055)	0.194 (0.058)	0.171 (0.035)	0.199 (0.039)	-0.161 (0.048)	-0.194 (0.051)
Log(Rest of Hemisphere Current PC Sales Weighted by Processor Speed)	0.196 (0.088)		0.245 (0.040)		-0.274 (0.070)	
Log(Rest of Hemisphere PC Sales, Two Years' Ahead, Weighted by Processor Speed)		0.122* (0.133)		0.200 (0.073)		-0.210* (0.116)
Log (Rest of Hemisphere IDEMA Patent Stock, Top Three Patent Subcategories)	0.511 (0.165)	0.662 (0.168)	0.469 (0.215)	0.649 (0.217)	-0.562 (0.207)	-0.731 (0.237)
Product Age (in fractional years)	-0.376 (0.018)	-0.390 (0.023)	-0.315 (0.014)	-0.326 (0.021)	0.205 (0.018)	0.191 (0.023)
Firm Exit Within the Next Two Years (1 if yes, 0 if no)	-0.329 (0.124)	-0.358 (0.178)	-0.396 (0.099)	-0.415 (0.157)	0.226 (0.110)	0.207* (0.177)
Number of Observations	6,294	5,524	6,294	5,524	6,294	5,524
R^2	0.884	0.879	0.969	0.965	0.959	0.955
Root Mean Squared Error	0.591	0.578	0.326	0.333	0.429	0.425

Notes: Price per GB is the deflated average price (in 2005$) per unit of storage expressed in GB.